PMO Analysis of Cycloadditions, III[1]

Regioselectivity and Reactivity in Cycloadditions of Formonitrile Oxide

Reiner Sustmann* and Willi Sicking

Institut für Organische Chemie der Universität Essen,
Universitätsstraße 5, D-4300 Essen 1

Received March 6, 1987

Cycloadditions of formonitrile oxide are studied by an all-valence electron perturbation treatment. The activated complex is modeled according to the calculated transition state for the addition of formonitrile oxide to acetylene. The separation of the interaction energy in polar, noncovalent, and covalent contributions shows the type II behavior of formonitrile oxide in the classification scheme of 1,3-dipolar cycloadditions and demonstrates that the regioselectivity can be explained better by the noncovalent repulsion than by the frontier molecular orbital stabilisations. A discussion of regioselectivity in terms of the magnitude of the eigenvector coefficients in the FMOs does not give satisfactory results.

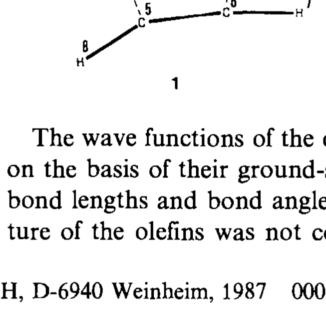
PMO-Analyse von Cycloadditionen, III[1]. – Regioselektivität und Reaktivität in Cycloadditionen des Formonitriloxids

Ein Allvalenzelektronen-Störungsverfahren wird auf Cycloadditionen von Formonitriloxid angewendet. Hierbei wird die Struktur des aktivierten Komplexes dem ab-initio-berechneten Übergangszustand der Reaktion von Formonitriloxid an Acetylen angepaßt. Aus der Aufteilung der Wechselwirkungsenergie in polare, nichtkovalente und kovalente Anteile erkennt man die Zugehörigkeit des Formonitriloxids zum Typ II der Klassifikation von Cycloadditionen. Die experimentell beobachtete Regioselektivität läßt sich besser mit nichtkovalenten Abstoßungen als mit der Stabilisierung durch die FMO-Wechselwirkungen erklären. Eine Deutung der Regioselektivität auf der Basis der Größe der Eigenvektorkoeffizienten in den Grenzorbitalen ist nicht erfolgreich.

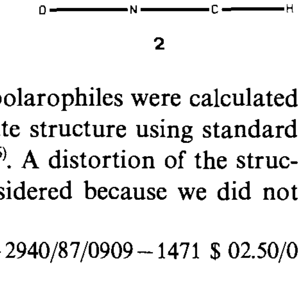
Cycloadditions of nitrile oxides have been studied for many years[2]. After the pioneering work of Quilico, Grünanger and their collaborators[2,3], Huisgen and his group studied the regioselectivity and reactivity of these 1,3-dipolar cycloadditions in detail[4–8]. A FMO theoretical rationalisation of reactivity[9] and regioselectivity[10,11] seemingly ended this chapter of Organic Chemistry. This conclusion, however, may be erroneous. The presumable conclusive rationalisation of regioselectivity may turn out to be not as final as it may have been assumed.

In this contribution we concentrate on the aspect of regioselectivity and reactivity in 1,3-dipolar cycloadditions of formonitrile oxide to olefins and alkynes. We use the recently developed all-valence electron perturbation program PERVAL[12] based on the MINDO/3 approximation, to analyse the transition state fo these cycloadditions. The results of a study of the transition state of the reaction of acetylene with formonitrile oxide provide the basis[1]. Here we found that PMO theory can be applied to the interaction of two molecules at separations which are identical to those in the ab-initio calculated transition state[13]. It was demonstrated that a type II behavior of formonitrile oxide according to the cycloaddition classification[9] is observed if distortions of the molecules analogous to those in the ab-initio transition-state structure are taken into account. In contrast, linear formonitrile oxide showed FMO interactions of very different strength, $\text{HOMO}_{\text{HCNO}}$-$\text{LUMO}_{\text{HCCH}}$ being predominant. If formonitrile oxide would behave experimentally like benzonitrile oxide[7], a type II 1,3-dipole, we expect, however, two energetically comparable FMO interactions. As the replacement of hydrogen by a phenyl group in going from formonitrile oxide to benzonitrile oxide should not alter the reactivity behavior drastically, the above result for undistorted formonitrile oxide casts doubts on the usefulness of undistorted structures in discussions of reactivity and regioselectivity.

Calculational Procedures and Transition-State Model: The perturbation program PERVAL calculates the interaction between two molecules K and L on the basis of their MINDO/3 wave functions and divides the energy into polar, non-covalent, and covalent interactions[12,14,15]. The calculations are carried out on an IBM AT personal computer and analysed graphically. The results of our study of the transition state of the cycloaddition of formonitrile oxide to acetylene, which were based on an ab-initio study[13] motivated us to apply this transition-state structure to other cycloadditions of formonitrile oxide. In the following, the perturbation calculations are based on the structure of formonitrile oxide as in the transition state of its reaction with acetylene (1)[13].



1



2

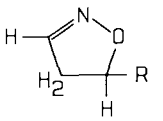
The wave functions of the dipolarophiles were calculated on the basis of their ground-state structure using standard bond lengths and bond angles[16]. A distortion of the structure of the olefins was not considered because we did not

0009–2940/87/0909–1471 $ 02.50/0

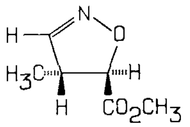
want to introduce ambiguous and undefined parameters. The transition-state structure for the calculation then is as shown in **2**, the distance *r* between the C atom of formonitrile oxide and the line connecting the carbon atoms of the CC double bond is chosen to 250 pm (see **2**), slightly greater than the ca 220 pm in the ab-intio transition state. A through D stand for the substituents of the dipolarophiles (see Table 1). The CC double bond is placed symmetrically with respect to the nitrile oxide unit. In the case of alkynes as dipolarophiles we apply the same transition-state structure, replacing the olefin by the corresponding alkyne.

Cycloadditions of Formonitrile Oxide

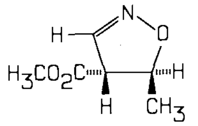
The behavior of unsubstituted 1,3-dipoles in cycloadditions is of special interest because it allows to exclude steric effects which are often difficult to assess. Although the number of cycloaddition reactions of formonitrile oxide is limited, their analysis might provide insight into other than steric contributions to regioselectivity. Whereas monosubstituted olefins like methyl acrylate and styrene form a single 5-substituted 2-isoxazoline (**3** and **4**), with methyl crotonate the formation of regioisomers, **5** and **6** in the ratio 62:38, is observed. Methyl cinnamate yields the regioisomers **7** and **8** in the ratio 24:76.



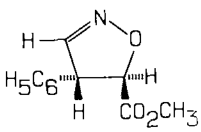
3: R=CO_2CH_3
4: R=C_6H_5



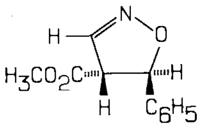
5



6

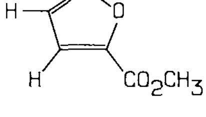


7

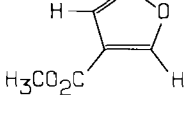


8

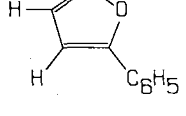
In contrast to methyl acrylate it was found that methyl propiolate gave a mixture of the regioisomers **9** and **10** in the ratio 72:28. Phenylacetylene, on the other hand, behaves like styrene forming only the 5-substituted isoxazole **11**.



9



10



11

Results

In Figure 1 we compare the structure and energies of the π- and pseudo π-MOs of bent and linear formonitrile oxide. The program PERVAL represents the orbitals at the individual atoms as linear combinations of s and p contributions. In this way it becomes apparent that the bending generates orbitals not only of pure p but also of mixed s and p character. This leads to orbitals which are oriented towards the dipolarophile in the transition state. It is interesting to note how the polarisation of the MOs changes on bending. In Φ_1 bending does not alter the polarisation appreciably, in Φ_2 (HOMO) the contributions of the C atom increases slightly at the expense of the N atom of formonitrile oxide and in Φ_3 (LUMO) we notice a bigger contribution from oxygen. In the latter the bending causes incorporation of s character at the C and N atom with the consequence of unequal extensions of the orbital lobes. In particular the orbital at N develops a bigger lobe opposite to the approaching dipolarophile.

On the basis of the structure **2** for the reactive complex, we have carried out PMO calculations for the reaction of formonitrile oxide with methyl acrylate, methyl crotonate, styrene, and methyl propiolate. In all cases we considered both possible orientations. Even though no kinetic data exist for the cycloadditions of formonitrile oxide we will analyse its reactivity and we will include for this purpose methyl vinyl ether, propene, butadiene, methyl methacrylate, and acrylonitrile. Kinetic data for cycloadditions of benzonitrile oxide will serve for comparison[7)]. The range from electron-rich to electron-deficient dipolarophiles should make it possible to demonstrate the position of formonitrile oxide within the classification scheme for cycloadditions. For some examples we will compare the results with calculations for linear formonitrile oxide.

In Table 1 we present the perturbation energies as polar, noncovalent, and covalent contributions together with the two FMO interactions. It is recognized immediately that the polar contributions are small, being responsible for less than 10% of the total energy. For some cases they are positive (repulsive) and for others negative (attractive). No correlation of these values with the experimentally observed regioselectivity can be found. More important is the noncovalent interaction. Here we find smaller values for the 5-substituted than for the 4-substituted 2-isoxazoline for all monosubstituted olefins. In cases where experimental results are available these coincide with the observations.

As this result can be rationalised for all dipolarophiles in a similar way it is sufficient to display the noncovalent interaction as atom contributions for methyl acrylate in both orientations. The area of the circles in **12** and **13** represents the magnitude of the atom contribution to the noncovalent energy[1,12)] in the same scale for both complexes. The numbers in **12** and **13** indicate the values for the total repulsion and the highest (Max.) contributation of a single atom.

The difference between **12** and **13** derives from the influence of the substituent. Its interaction with the carbon atom of formonitrile oxide is greater than with the oxygen atom. Particularly, the C atom of the carbonyl group in **13** exhibits greater repulsive interactions with the C atom of formonitrile oxide than with the oxygen atom in orientation **12**. As a consequence the contribution of the carbon atom of formonitrile oxide is also slightly greater in **13** than in **12**. Therefore, in terms of the noncovalent interaction the com-

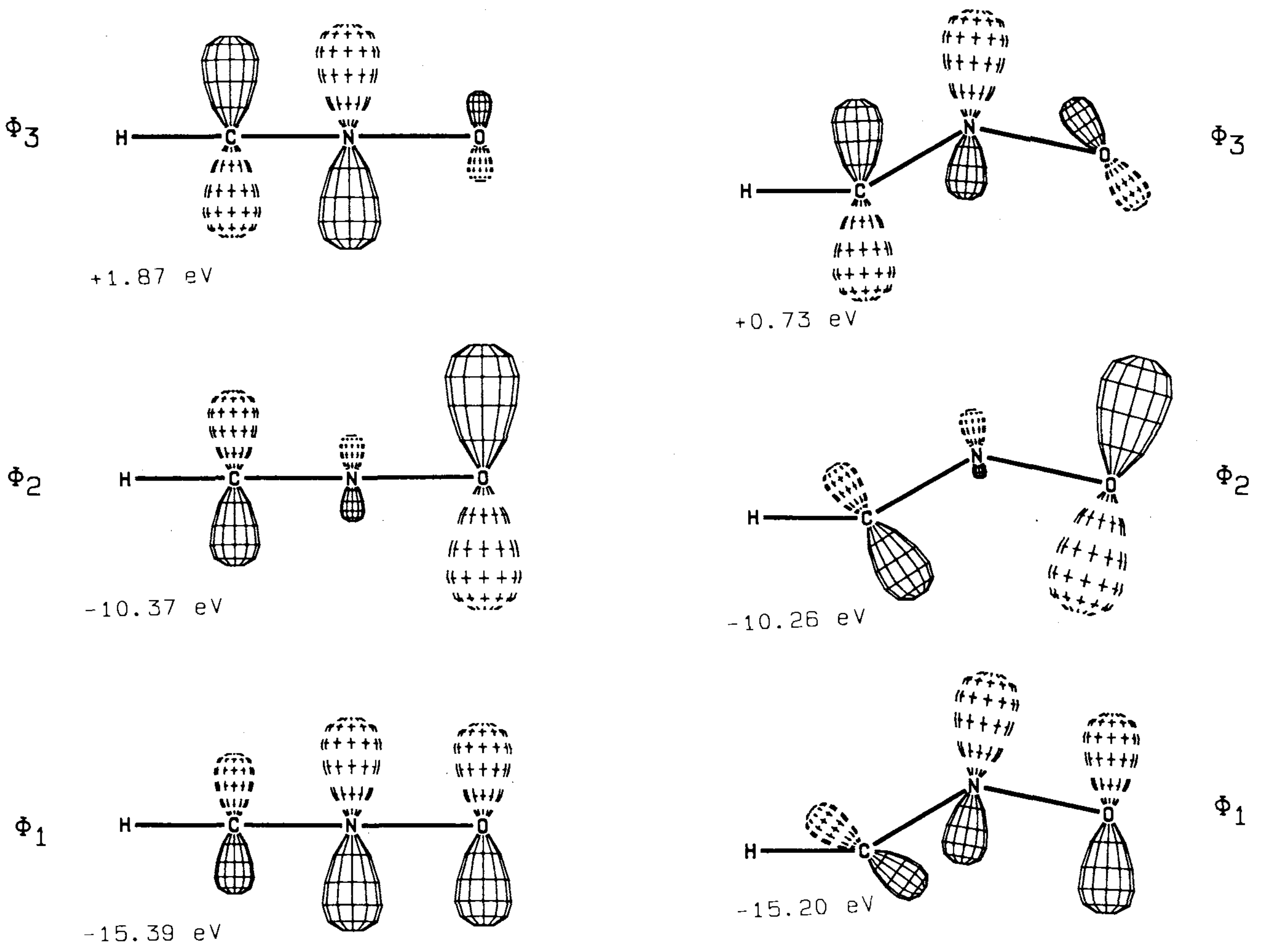
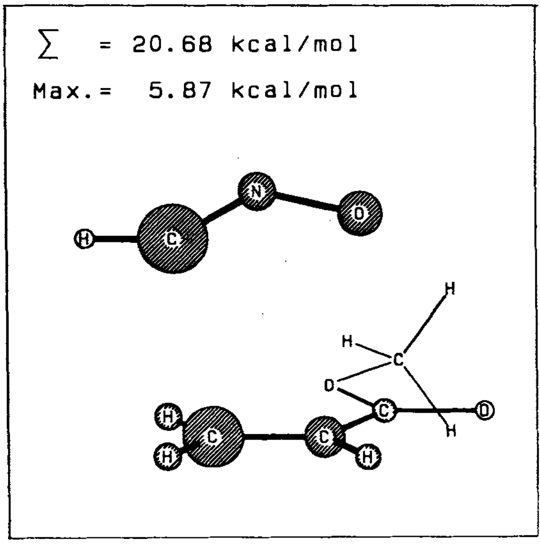


Figure 1. π- and pseudo π-MOs involved in the 1,3-dipolar cycloaddition of linear and bent formonitrile oxide

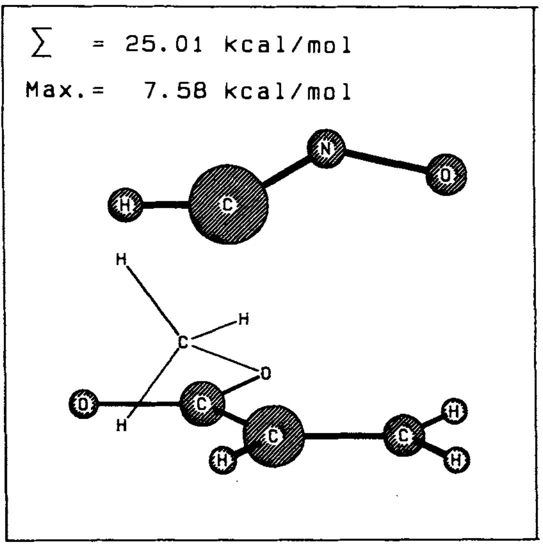
Table 1. Perturbation energies for the interaction of formonitrile oxide with dipolarophiles in complexes of structure **2** (kcal/mol)

A	B	C	D	Polar	Non-cov.	Cov.	Sum	HO_{HCNO}-LU_{olefin}	HO_{olefin}-LU_{HCNO}	$Sum_{HO\text{-}LU}$
H	H	H	CO_2CH_3	0.74	20.68	−5.41	16.01	−1.44	−1.36	−2.80
H_3CO_2C	H	H	H	−1.66	25.10	−5.76	17.68	−1.24	−1.24	−2.48
H_3C	H	H	CO_2CH_3	−0.20	28.16	−6.17	21.79	−1.27	−1.16	−2.43
H_3CO_2C	H	H	CH_3	−1.08	28.78	−5.72	21.98	−1.00	−1.14	−2.14
H	H	CH_3	CO_2CH_3	−0.68	24.22	−5.38	18.16	−1.27	−1.16	−2.43
H_3C	CO_2CH_3	H	H	−0.60	32.72	−6.64	25.48	−1.07	−1.16	−2.23
H	H	H	CN	0.02	19.26	−5.18	14.10	−1.17	−1.36	−2.53
CN	H	H	H	−0.41	23.25	−5.65	17.19	−1.11	−1.29	−2.40
H	H	H	$CH{=}CH_2$	0.05	20.46	−5.04	15.37	−1.07[a]	−1.84[b]	−2.91
$H_2C{=}HC$	H	H	H	−0.07	25.41	−5.53	19.95	−1.04[a]	−2.21[b]	−3.25
H	H	H	OCH_3	−0.45	22.52	−5.22	16.85	−0.86	−1.98	−2.84
H_3CO	H	H	H	0.62	27.12	−6.10	21.64	−0.96	−0.83	−1.79
H	H	H	CH_3	−0.11	22.47	−5.23	17.13	−1.03	−1.73	−2.76
H_3C	H	H	H	0.12	25.76	−5.73	20.15	−0.96	−1.12	−2.08
H	H	H	C_6H_5	−0.14	20.68	−4.92	15.62	−1.03[a]	−1.67[b]	−2.70
C_6H_5	H	H	H	0.13	26.12	−5.37	20.77	−0.98[a]	−1.59[b]	−2.57
H	–	–	CO_2CH_3[c]	0.43	18.17	−4.67	13.93	−0.99	−0.84	−1.83
H_3CO_2C	–	–	H[c]	−1.40	26.29	−6.18	18.71	−0.83	−0.64	−1.47

[a] Sum of the interaction of $HOMO_{HCNO}$ with two π*-MOs of the olefin. – [b] Sum of the interaction of two π-MOs with $LUMO_{HCNO}$. – [c] Methyl propiolate.



12



13

plex **12** is preferred over **13**. Methyl crotonate as a 1,2-disubstituted dipolarophile should be a good test case because it produces experimentally a mixture of the two possible regioisomers. It is the only dipolarophile in Table 1 with almost identical values for the noncovalent contribution in both orientations. We can rationalize this on the basis of the same argument which we used to explain the regiochemistry for methyl acrylate. Due to the substituents at each end of the double bond the extent of noncovalent interaction of the carbon atom of formonitrile oxide with the reacting atom and its substituent in methyl crotonate, either methyl or methoxycarbonyl, is very similar for both regioisomers. The main factor for this equilibration is the carbon atom of the substituents which is directly bonded to the reacting centre. The noncovalent interaction decreases rapidly with distance, so that other atoms of the substituents, being farther away from the terminal atoms of formonitrile oxide, do not show a significant influence.

Methyl propiolate is an example which does not seem to fit in this otherwise "perfect" picture. In the reaction of this dipolarophile with formonitrile oxide a mixture of regioisomers is observed with a preference for the 5-substituted one. Although we predict a predominance for the 5-substituted 2-isoxazole by the noncovalent interaction the difference in the values for the two isomers seems to be exaggerated. It may be that we encounter here the limit of the applicability of the assumed transition-state structure. At some point along the reaction coordinate distortions of the dipolarophiles will become important.

A very satisfying picture of the reactivity can be derived if we assume that formonitrile oxide behaves similar to benzonitrile oxide. For all examples (Table 1) we note comparable contributions for both HOMO-LUMO interactions which classifies formonitrile oxide as a type II 1,3-dipole. This is exactly what one expects on the basis of the experimental results for benzonitrile oxide. Furthermore, we observe for electron-deficient olefins slightly higher contributions from the interaction $HOMO_{HCNO}$-$LUMO_{olefin}$, whereas for the electron-rich methyl vinyl ether the stabilisation $HOMO_{olefin}$-$LUMO_{1,3\text{-dipole}}$ exceeds the other by a factor of two. Would we have predicted this on the basis of the energies of the frontier molecular orbitals according to the MINDO/3 calculations? In Figure 2 we take methyl acrylate and methyl vinyl ether as an example.

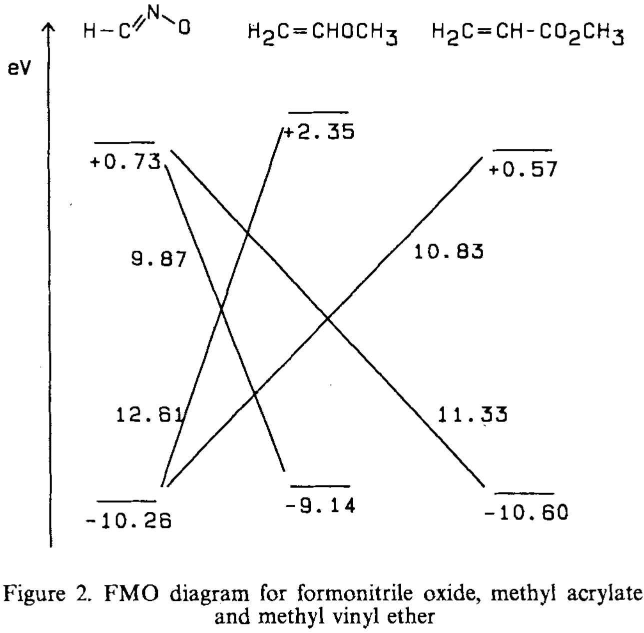


Figure 2. FMO diagram for formonitrile oxide, methyl acrylate, and methyl vinyl ether

No clear answer as to which FMO interaction is more important can be deduced for methyl acrylate, the two HOMO-LUMO separations are very similar. This supports the conclusion from the stabilisation energies but it is in

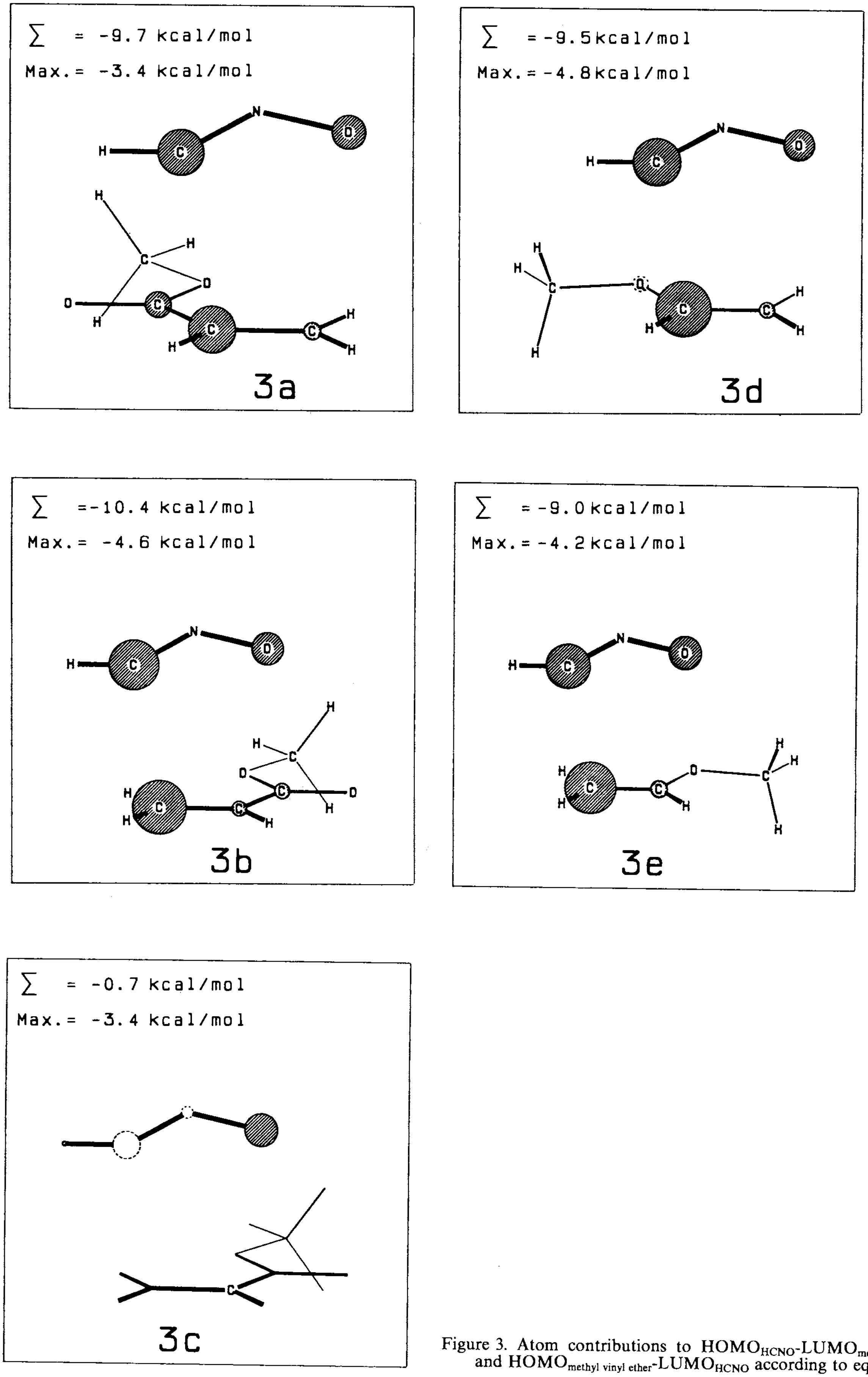


Figure 3. Atom contributions to HOMO$_{\text{HCNO}}$-LUMO$_{\text{methyl acrylate}}$ and HOMO$_{\text{methyl vinyl ether}}$-LUMO$_{\text{HCNO}}$ according to eq. (1)

contrast to the expectation from the kinetic measurements for benzonitrile oxide which suggest a superior interaction $\text{HOMO}_{\text{HCNO}}$-$\text{LUMO}_{\text{methyl acrylate}}$. The implication is that it might be dangerous to deduce a FMO energy scheme from kinetic data. Particularly in the case of a type II 1,3-dipole it is the sum of the two FMO stabilisations which has to be considered. On this basis both the electron-deficient methyl acrylate and the electron-rich methyl vinyl ether show comparable stabilisations, i. e. they should exhibit similar reactivities. In the case of methyl vinyl ether a smaller gap for $\text{HOMO}_{\text{vinyl ether}}$-$\text{LUMO}_{\text{HCNO}}$ is observed and this is in line with our expectation of a greater $\text{HOMO}_{\text{olefin}}$-$\text{LUMO}_{\text{HCNO}}$ interaction.

Figure 3 analyses the atom contributions to the HOMO-LUMO interactions for methyl acrylate and methyl vinyl ether. The area of the circles characterises the contribution of individual atoms to the numerator of the FMO interaction according to eq. (1).

$$\Delta E^{m}_{\text{HO-LU}} = -1/2 \sum_{n} \sum_{\kappa} \sum_{\lambda} c_{\text{HO}\lambda}\, c_{\text{LU}_\kappa}\, \beta_{\kappa\lambda} \qquad (1)$$

For any atom m of one molecule the summation is carried out over all atoms n of the other molecule. κ and λ are the

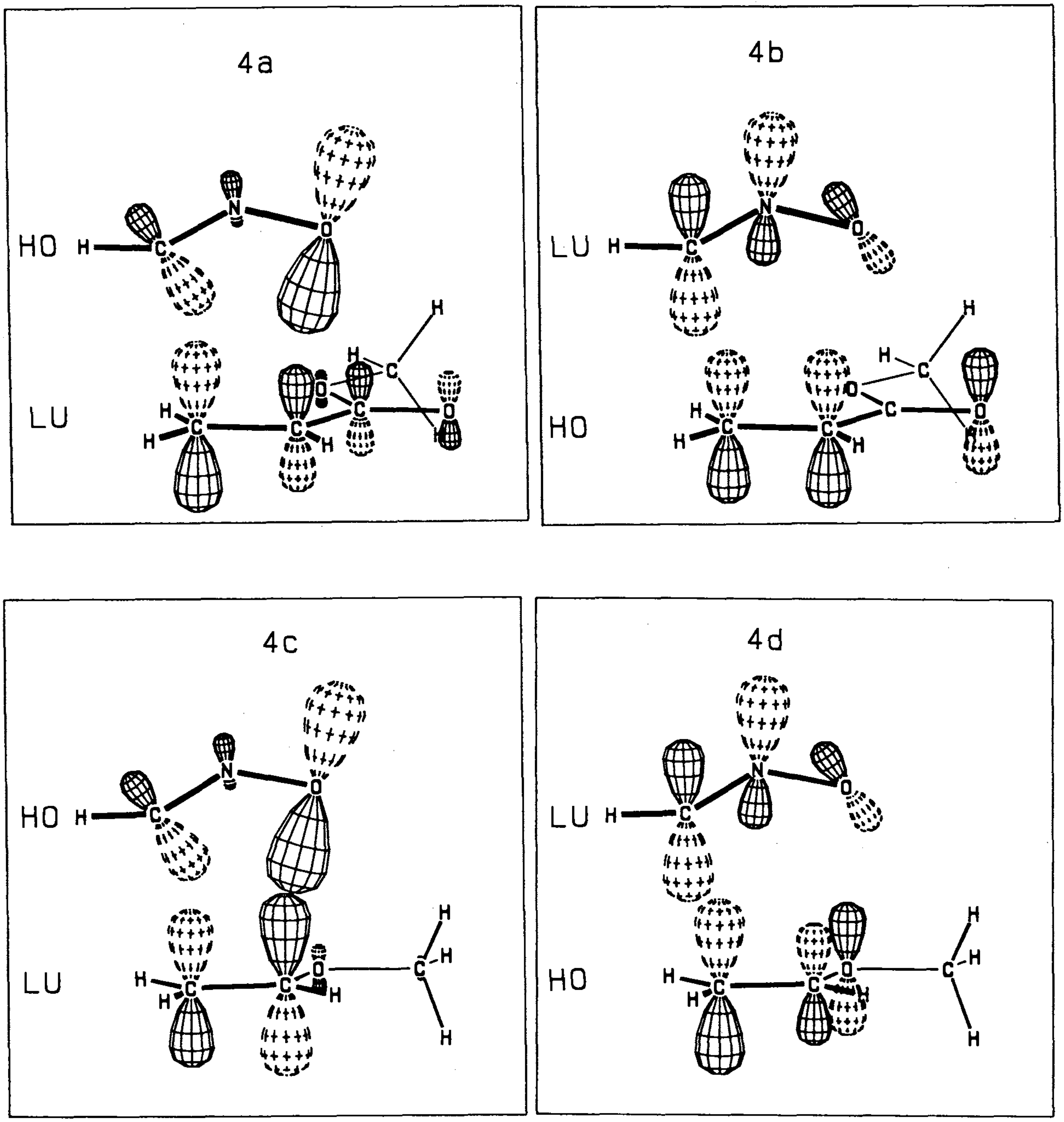


Figure 4. Representation of the overlap of the HOMO-LUMO pairs for formonitrile oxide with methyl acrylate and methyl vinyl ether

indices of the atomic orbitals of the atoms m and n. The sign of this quantity may be either positive or negative, i.e. in the calculation of the numerator of the HOMO-LUMO interaction[12,14)] they may either accumulate to a high value, signalising strong bonding, or compensate each other which will lead to a small total bonding. The atoms which are not encircled in Figure 3 contribute less than the area of a circle with a radius half of the size of the element symbol.

The analysis of the atom contributions to the covalent interaction in $\mathrm{HOMO_{HCNO}}$-$\mathrm{LUMO_{methyl\ acrylate}}$ and $\mathrm{HOMO_{methyl\ vinyl\ ether}}$-$\mathrm{LUMO_{HCNO}}$ shows for both dipolarophiles in both orientations greater contributions from the atoms forming the CC bond, i.e. they indicate unsymmetrical bond formation. We have displayed in Figure 3c the individual elements of the sum of eq. (1) for the C atom of methyl acrylate next to the substituent, i.e. in an orientation which gives the 5-substituted 2-isoxazoline. There is bonding interaction with the oxygen atom of formonitrile oxide but this is compensated by contributions of opposite sign from the nitrogen and carbon atom. The net result is that this carbon atom does not produce appreciable bonding by this HOMO-LUMO interaction. The small circle in Figure 3b is the pictorial representation for this situation.

Which regiochemistry can be predicted by the covalent stabilisation, in particular by the interaction of the frontier molecular orbitals? We will take methyl acrylate and methyl vinyl ether as examples. It is pleasing to see that the stronger FMO interaction (see Table 1) favors the 5-substituted 2-isoxazoline for methyl vinyl ether. For methyl acrylate both FMO stabilisations agree with the experimental regiochemistry even though the differentiation is small. The sum of both interactions confirms this picture. This conclusion is based on the total bonding contribution, i.e. the interaction of all atoms of one molecule with all atoms of the other. In the accepted explanation of regiochemistry one concentrates on the atoms, which are involved in the bond-forming process, and analyses the magnitude of the eigenvector coefficients in the predominant HOMO-LUMO interaction. This amounts to a qualitative interpretation of parts of eq. (1). The products of the eigenvector coefficients for the atoms, which are covalently bound, are selected and it is assumed that the corresponding $\beta_{\kappa\lambda}$ values are equal. One should then observe that orientation where the sum of the products of the coefficients is greater than for the inverse regiochemistry. As Houk[10)] showed this is the case if the bigger or smaller coefficients, resp., are combined with each other. We demonstrate this procedure for the HOMO-LUMO interactions of formonitrile oxide with methyl acrylate and methyl vinyl ether in Figure 4 where only the orientation leading to the 5-substituted 2-isoxazoline is pictured.

Houk et al.[17)] noted that bending of formonitrile oxide leads to an increase of the contribution of the C atom in the HOMO, thus diminishing its polarisation in the bent structure (compare Figure 1). The prescription to combine the big lobes or the small ones, resp., of the HOMO and LUMO of the reactants does not indicate the preferred regioisomer for methyl acrylate. In the $\mathrm{HOMO_{methyl\ acrylate}}$-$\mathrm{LUMO_{HCNO}}$ interaction it is the almost identical contribution of the C atoms of the double bond in methyl acrylate which prohibits any prediction. The other HOMO-LUMO pair would suggest the experimentally not observed regioisomer. Therefore, we have to conclude that the simple model does not work for methyl acrylate. The polarisation of $\mathrm{HOMO_{vinyl\ ether}}$ and $\mathrm{LUMO_{HCNO}}$ does match in the orientation which produces the 5-substituted isomer. Here, the simple model and our procedure, which takes into account all interactions explicitely, work in the same direction.

Next we consider styrene in detail because it is a dipolarophile with an extended π system. Such molecules present special problems as several MOs can participate in the intermolecular interaction. It is questionable to pick out only one interaction and identify the complete behaviour of the system with it. In Figure 5 we display for the two addition modes of styrene to formonitrile oxide the interaction of HOMO and LUMO of the 1,3-dipole with two unoccupied and occupied π-MOs of styrene. The latter orbitals derive from the union of the bonding and antibonding orbital of the double bond with the π system of benzene. The energies of these MOs and the amount of stabilisation which results from each interaction is given in Figure 5.

Several features can be recognized: 1. In three cases we find that formonitrile oxide, either the HOMO or the LUMO, shows similar stabilisations with both π-MOs of styrene. In the fourth case one interaction is much stronger, but this is not the HOMO-LUMO pair. 2. The selection of a particular orbital pair and the derivation of a preferred regiochemistry on this basis would be rather arbitrary. 3. The summation over the π interactions for both regioisomers leads to almost equal contributions of $\mathrm{HOMO_{HCNO}}$-π^*-$\mathrm{MOs_{styrene}}$ and π-$\mathrm{MOs_{styrene}}$-$\mathrm{LUMO_{HCNO}}$ (see Table 1). Not even the analysis of these numbers indicates an explicit preference for one of the regioisomers. In contrast to the experimental observation we would, therefore, anticipate the formation of a mixture of isomers. On the other hand (see above), the noncovalent contribution rationalizes the experimental result correctly.

For the cycloadditions of formonitrile oxide both HOMO-LUMO interactions turn out to be of similar importance. A better measure of regioselectivity in such a case might be the sum of both stabilisations. For those dipolarophiles where experimental results are available this seems to be the case. Not only do we expect the 5-substituted 2-isoxazoline for methyl acrylate but we also would predict that methyl crotonate favors the 5-methoxycarbonyl-substituted isomer. Therefore, we may conclude that the sum of both FMO stabilisations constitutes a better measure for regioselectivity in those cases where none of the HOMO-LUMO interactions obviously predominate. However, not too much emphasis should be put on this point because the amounts of stabilisation for the regioisomers are generally not very different.

We have also performed perturbation calculations for molecular complexes of linear formonitrile oxide with the same set of dipolarophiles assuming a symmetrical approach of 1,3-dipole and olefin as shown in **14**.

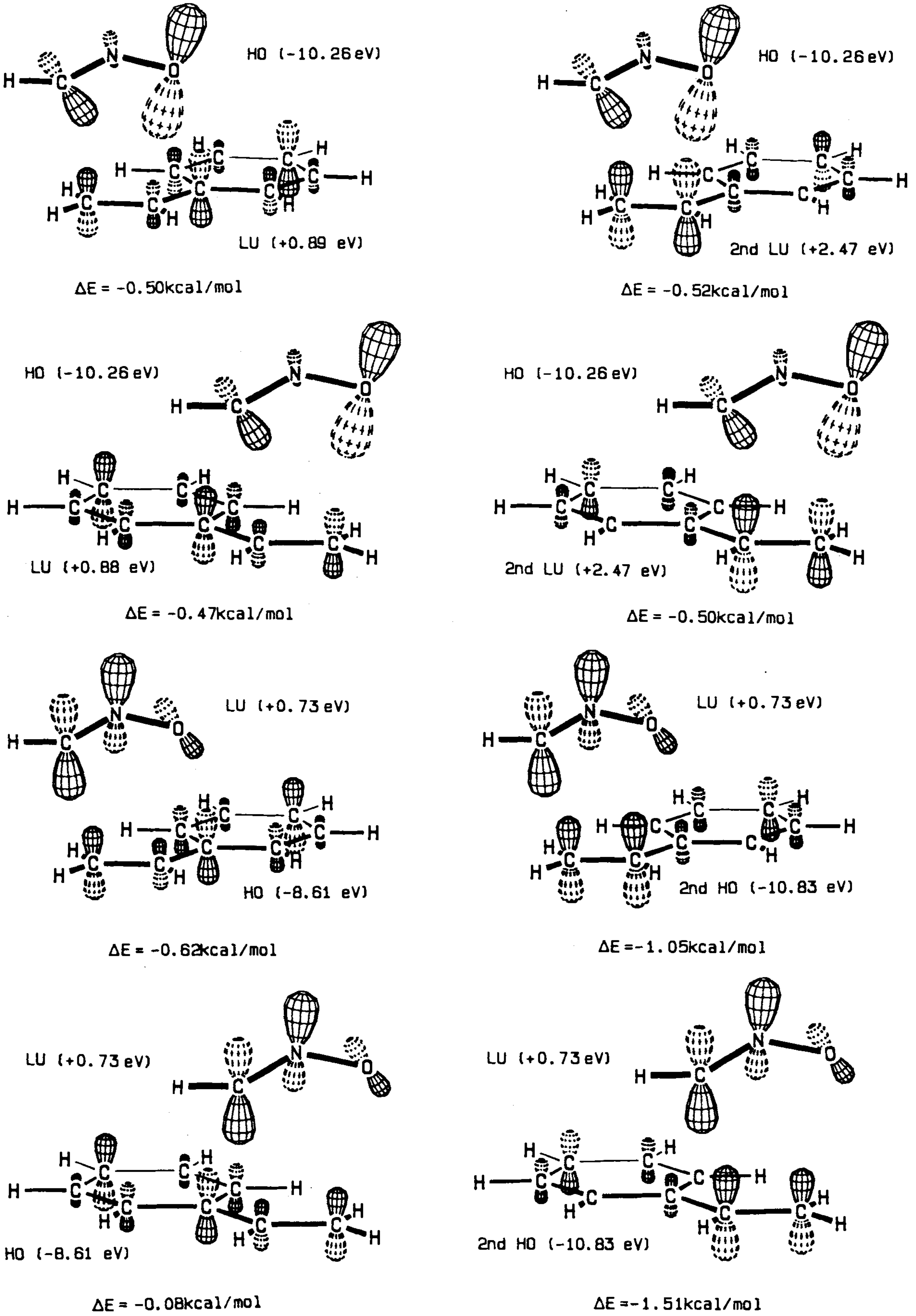
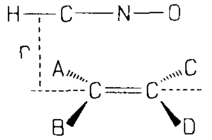


Figure 5. Analysis of orbital interactions in the cycloaddition of styrene to formonitrile oxide

Table 2. Perturbation energies for complexes of linear fulminic acid with dipolarophiles according to **14** (kcal/mol)

A	B	C	D	Polar	Non-cov.	Cov.	Sum	$\mathrm{HO_{HCNO}\text{-}LU_{olefin}}$	$\mathrm{HO_{olefin}\text{-}LU_{HCNO}}$	Sum
H	H	H	OCH_3	−0.71	37.52	−3.98	32.83	−1.59	−0.001	−1.59
OCH_3	H	H	H	0.61	39.69	−5.34	34.96	−1.78	−0.10	−1.88
H	H	H	CO_2CH_3	1.43	33.70	−5.10	30.03	−2.80	−0.01	−2.81
CO_2CH_3	H	H	H	−1.03	37.26	−5.03	31.20	−2.38	−0.03	−2.41
CH_3	H	H	CO_2CH_3	0.62	42.24	−5.60	37.26	−2.26	−0.11	−2.37
CO_2CH_3	H	H	CH_3	−0.70	43.79	−5.12	37.97	−1.91	−0.02	−1.93



14

The main difference to the results with formonitrile oxide in the bent structure is that regardless of the nature of the olefin the interaction $\mathrm{HOMO_{HCNO}\text{-}LUMO_{olefin}}$ is always prevailing, the other one being negligible. Three examples are given in Table 2. It is easy to explain why such a great difference in the FMO interactions exists. The LUMO of formonitrile oxide (see Figure 1) has a high contribution from the central nitrogen atom in the linear and in the bent structure. Its contribution to the LUMO is of opposite phase than those from the carbon and oxygen atom. Our valence-electron perturbation treatment not only considers the reacting atoms but it includes the others as well. If we place an olefin symmetrically below formonitrile oxide as in **14**, we observe compensating interactions. The bonding which arises from the interaction between the reacting atoms is counteracted by interactions of opposite (antibonding) sign between the central nitrogen atom and the carbon atoms of the dipolarophile. We recognize one reason for the bending of formonitrile oxide in this destabilising contribution: the distance between the nitrogen atom and the C atoms of the double bond increases, the overlap is diminished and the compensating effect in the interaction disappears. In addition the nonequivalent extension of the orbital lobes at N in the LUMO of bent HCNO are favorable with respect to a decrease of its antibonding influence. On the other hand in $\mathrm{HOMO_{HCNO}}$ the contribution of the nitrogen atom is small and it does not take part in the HOMO-LUMO interaction. This discussion emphasizes again how careful the structure of the molecular complex to be studied has to be selected.

The HOMO-LUMO interactions in **14** do not characterize formonitrile oxide to be a type II 1,3-dipole. The noncovalent interaction, however, is reproduced in a similar way as for complexes of structure **2**. Taking the noncovalent interaction as a measure of regioselectivity we would have arrived at the same conclusions as with the nonlinear formonitrile oxid, the experimental trend being reproduced. Contrary, considering the HOMO-LUMO interactions to be the decisive factor, we must conclude that a discussion of regioselectivity with the linear formonitrile oxide is not very meaningful.

Conclusion: The analysis of cycloadditions of formonitrile oxide by perturbational methods has revealed features which seem to be important for a discussion of regiochemistry and reactivity in terms of the FMO model. The FMO interactions in a model transition state with undistorted formonitrile oxide do not parallel those in the bent structure which derives from ab-initio calculations. In cases where the eigenvector coefficients in the FMOs of linear formonitrile oxide allow a rationalisation of regioselectivity this may be fortuitous. An improvement in the structure of the model transition state and in the theoretical model seems to be required. The availability of structures for transition states which were obtained by elaborate calculations offers a possibility to choose model complexes. We also suggest that PMO calculations of the type presented here constitute an improvement over the simple FMO model. However, whenever possible the simplest approach should be retained as it is normally also the most elegant one. Our PMO procedure includes FMO theory and therefore allows to recognise where it can be applied safely. Further studies on cycloadditions of other 1,3-dipoles are in progress.

This work was supported by the *Deutsche Forschungsgemeinschaft*.

CAS Registry Numbers

$CH\equiv NO$: 51060-05-0 / $CH_2=CHCO_2Me$: 96-33-3 / $MeCH=CHCO_2Me$: 623-43-8 / $CH_2=CMeCO_2Me$: 80-62-6 / $CH_2=CH\text{-}CN$: 107-13-1 / $CH_2=CHCH=CH_2$: 106-99-0 / $CH_2=CHOMe$: 107-25-5 / $CH_2=CHMe$: 115-07-1 / $PhCH=CH_2$: 100-42-5 / $CH\equiv CCO_2Me$: 922-67-8

---

[1] Part II: R. Sustmann, W. Sicking, *J. Am. Chem. Soc.*, submitted for publication.

[2] P. Caramella, P. Grünanger in *1,3-Dipolar Cycloadditions*, A. Padwa ed., Vol. 1, p. 291, Wiley-Interscience, New York 1984.

[3] A. Quilico, G. Stagno d' Alcontres, P. Grünanger, *Gazz. Chim. Ital.* **80** (1950) 479; for subsequent papers see ref.[2].

[4] K. Bast, M. Christl, R. Huisgen, W. Mack, R. Sustmann, *Chem. Ber.* **106** (1973) 3258.

[5] M. Christl, R. Huisgen, R. Sustmann, *Chem. Ber.* **106** (1973) 3275.

[6] R. Huisgen, M. Christl, *Chem. Ber.* **106** (1973) 3291.

[7] K. Bast, M. Christl, R. Huisgen, W. Mack, *Chem. Ber.* **106** (1973) 3312.

[8] M. Christl, R. Huisgen, *Chem. Ber.* **106** (1973) 3345.

[9] R. Sustmann, *Tetrahedron Lett.* **1971**, 2717; *Pure Appl. Chem.* **40** (1974) 569.

[10] K. N. Houk, *J. Am. Chem. Soc.* **94** (1972) 8953; K. N. Houk, J. Sims, C. R. Watts, L. J. Luskus, *ibid.* **95** (1973) 7301; K. N. Houk, J. Sims, R. E. Duke jr., R. W. Strozier, J. K. George, *ibid.* **95** (1973) 7287.

[11] J. Bastide, O. Henri-Rousseau, *Bull. Soc. Chim Fr.* **1973**, 2294; J. Bastide, N. El Ghandour, O. Henri-Rousseau, *ibid* **1973**, 2290.

[12] R. Sustmann, W. Sicking, *Chem. Ber.* **120** (1987) 1323,

[13] A. Komornicki, J. D. Goddard, H. F. Schaefer, III, *J. Am. Chem. Soc.* **102** (1980) 1763.

[14] R. Sustmann, A. Ansmann, F. Vahrenholt, *J. Am. Chem. Soc.* **94** (1972) 8099.

[15] R. Sustmann, F. Vahrenholt, *Theor. Chim. Acta* **29** (1973) 305.

[16] *Interatomic Distances,* Suppl. Specl. Publ. No. 18, The Chemical Society, London 1965.

[17] P. Caramella, R. W. Gandour, J. A. Hall, C. G. Deville, K. N. Houk, *J. Am. Chem. Soc.* **99** (1977) 385.

[79/87]